EMPOWERING STUDENTS TO LEARN HOW TO LEARN: MASS CUSTOMIZATION OF A GRADUATE ENGINEERING DESIGN COURSE

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ABSTRACT: ME 6101: Engineering Design is a graduate level course offered through the George W. Woodruff School of Mechanical Engineering at the Georgia Institute of Technology. To empower students to learn how to learn, the orchestrators of ME 6101 strive to offer an individual course in a group setting. In this paper, the techniques utilized to create this type of learning environment are described in terms parallel to those of the mass customization paradigm. Excerpts from students' essays are presented as anecdotal evidence that the concerted use of these methods aids and empowers students both in the internalization of course content and the development of critical analysis, abstraction, and synthesizing skills that will help them become lifelong learners.

KEY WORDS: Engineering Design Education • Mass Customization of Education • Learning How to Learn.

I. MASS CUSTOMIZATION AS A PEDAGOGICAL GOAL

"Nothing endures but change." Heraclitus

"The only thing that will never fail us is learning." Leornardo da Vinci

Wayne Gretsky was once asked if there was a secret to his success as a hockey player. He simply said, *"I skate to where the puck is going to be, not where it's been."*

Heraclitus was prescient in his observation about change, Leonardo in his musing provides us educators with a core principle to respond to change, and Gretsky the ultimate objective. We do recognize that there are many issues that need to be addressed in higher education; in this paper we focus on one, namely, that of empowering students to learn how to learn.

In their key-note address in 1985 Mistree and Muster laid out what they saw as some of the factors that are essential for creating the ambience for learning in 21st Century [1]. One of these factors was the empowerment of students to learn how to learn. They opined that it was not sufficient to only *teach* students the theory, tools, and methods of the field, but to also provide opportunities that *empower* them to learn how to learn.

This, we believe, is the *principal issue* that faces educators today. Accordingly, the question we address is the following:

How can we empower students to learn how to learn?

In this paper, we explore this critical issue recognizing the observation of *Heraclitus*, the musing of *Leonardo,* and the objective enunciated by *Gretsky* – to skate to where our puck - in an era defined by change - is likely to going. In our case we see our puck being guided by the *mantra* "an individual course in a group setting." To achieve this we embrace the notion of mass-customization of a course. Within this approach arise many new and interesting issues listed in Section I.C and further explored herein. In Section I.A we provide a brief overview of the mass-customization paradigm in order to draw parallels between it and the design of a course in Section I.B.

A. What is Mass Customization?

"You can have any color you want so long as it's black." These immortal words of Henry Ford regarding his Model T serve as the motivation for most advocates of mass customization. Ever since GM's Alfred Sloan began offering different styles of automobiles, companies have utilized product variety as a means of achieving competitive advantage. In today's market, customers are able to purchase endless amounts of customized products with varying degrees of variety. From blue jeans to tennis shoes, from retainers to cell-phone covers, from different colored i-Macs to modularly constructed Dell computers, customers are now expecting customized goods at reasonable prices.

This increase in demand for personalized products has manufacturing enterprises searching for design, manufacturing, and assembly methods that meet expectations efficiently. This paradigm shift – *mass customization* – is the ability to customize products quickly for individual customers or for niche markets with costs, efficiency, and speed approaching those of mass production [2]. Mass customized production involves building a product in response to a particular customer's expressed needs, as opposed to producing a product to be placed in an inventory with the expectation that some customer will later purchase it (mass production).

In this rather brief explanation of mass customization, we highlight two key points in order to relate it to the educational realm:

- Mass customization focuses on offering variety from a base product in order to satisfy customers' demand for personalized products.
- The paradigm of mass customization is built on various techniques and ideas that foster the ability to provide customized goods with minimal cost and lead-time.

It is in this context that we have developed our notion of offering an individual course in a group setting.

B. Individual Course in a Group Setting

Similar to their peers in industry, professors are faced with their own form of a design problem at the beginning of each term. Like any other engineering product, each component of a course must be thoroughly analyzed. What style of presentation will effectively convey the appropriate information? Which examples will be most illustrative for the students? What type of assignments will assist the student in

understanding the material? How will their understanding be tested and assessed? How can one manage the variety of students and their expectations? Perhaps most important: What should the students *take away* from the course? As in the case for designing for mass customization, components of the overall design must be tailored in order to satisfy varying customer demands.

In this paper, we discuss some orchestration techniques that can be implemented in different graduate engineering courses. These ideas are all geared towards the goal of offering a mass customized course – *an individual course in a group setting*. We explore the use of these techniques in a graduate engineering design course, ME 6101, offered each fall at the Georgia Institute of Technology.

ME 6101 is centered on the internalization of the systematic design methodology of Pahl and Beitz [3]. As the semester progresses students are involved in a myriad of games, interactive examples, and engaging activities to spark their creativity and their learning. Weekly "learning essays" provide students with the opportunity to articulate their learning. The semester closes with a series of lectures concerning current design methodology research and its role in the global marketplace. At the closure of the course, students submit three major documents: a report on their design project, an essay regarding the necessary augmentations of the Pahl and Beitz methodology to make it suitable for the future of design, and an essay on their learning throughout the semester. The mix of in-class and on-line (distance) students as well as the varied backgrounds and research interests of the students motivate the orchestration of an individual course in a group setting. A description of the class and its activities is presented in [4] wherein we describe, in the context of the Observe-Reflect-Articulate (ORA) learning construct,

multiple orchestration techniques. In this paper, we focus on the issues and instruments for orchestrating an *individual course in a group setting.*

C. Issues in Designing a Mass Customized Course

The customization of a course raises many issues. The following questions are foundational to our discussion of a learning environment suitable for orchestrating a course for an individual in a group setting:

- *How might a course be tailored to suit each student's individual needs and learning style?*
- *What sort of classroom environment and activities inspire students to become more active in their learning?*
- *How can students be taught to "learn how to learn" such that they can continue to educate themselves in the future?*

In this paper we present answers to the preceding questions in the context of our experiences with ME 6101. These answers are presented as descriptions of techniques of orchestration and how they have transformed the class into an individual course in a group setting. The relations among of these "orchestration instruments" to the questions listed above is illustrated in Table 1.

Table 1. Instruments of orchestration for a mass customized course

	How might a course be tailored to suit each student's individual needs and learning style?	What sort of classroom environment and activities inspire students to become more active in their learning?	How can students be taught to learn how to learn such that they can continue to educate themselves in the future?
Assignment 0	X	X	
O R A	X	X	X
Lecture	X		
In-class Discussion	X	X	
Learning Essays	X	X	X
Feedback	X		X
Best Practices	X	X	
Answer to Q4S	X	X	X
Semester Learning Essay	X	X	X
Self-grading Scheme	X	X	X

We do not intend to present *the* manner in which a course should be orchestrated, nor do we assume these techniques are applicable to all types of courses. Instead we present particular instruction methods that enabled us to individualize our course material and to encourage active involvement of students in their learning processes. Examples of student's writing are presented as anecdotal support for, or even counterpoints to, the material presented herein.

In Section II we discuss the fundamental mindset with which a professor must approach a mass customized course: understanding the student as an individual. Assignment 0 and the ORA learning construct are presented as the foundational pillars of this mass customized course. Multiple techniques of orchestrating a mass customized course are presented in Section III. The benefits for conducting an individual course in a group setting are presented in Section IV. Summary remarks are provided in Section V.

II. THE STUDENT AS AN INDIVIDUAL

A. Introduction to the Students of ME 6101

The views of students that took the class during the Fall 2001 semester are telling. Excerpts of assignments and essays are provided to articulate their thoughts about ME 6101. These comments appear throughout this paper as anecdotal notes on the material presented herein. We refer to these four graduate students by names that match their career ambitions, personal goals, or interests.

The Professor: A first-year graduate student, the "Professor" hopes to be just that – a college professor – and is pursuing a Ph.D. in mechanical engineering as a means to that end.

The Philosopher: This student has been nicknamed "The Philosopher" due to an interest in philosophy. This was evidenced in frequent references to Socrates in learning essays.

The Chief Executive: A first year graduate student, the "Chief Executive" desires to be the CEO of a company.

The Green Engineer: This first year graduate student has expressed passions for designing sustainable systems to lessen the impact of traditional products on the environment. This student has also expressed a desire to become a professor.

Additionally, comments from the Teaching Associate's experiences as a co-orchestrator of ME 6101 and as a previous student are included for further insight.

B. Assignment 0

Mass customization involves designing a product in response to customers' requirements. It is therefore crucial for the designer to have a thorough understanding of the demands, constraints, and bounds of the customers' specifications. The mass customization of ME6101 is no different.

During the first lecture of the course, students are given two handouts. The first is a traditional syllabus, much like those in other courses. The second handout, entitled "Assignment 0" constitutes the students' first challenge - to identify personal goals and aspirations for the semester and provide answers to the following questions:

- *Who are you?* Tell us a little about yourself. Describe in a few lines your academic background and work experience, favorite activities and hobbies, research and professional interests, etc.
- *Why are you here?*
- *List and prioritize five things you would like to achieve in this course.* Now analyze and make corrections.
- *What do you really want to achieve in this course?*

Student responses are encoded as web pages and posted on the course website[1] ([1] For access to the website for ME 6101, contact the corresponding author.). The use of standard web-oriented technologies enables the entire class to share and interact with one another. In this way, Assignment 0 allows students to learn both about themselves and their peers as they build a classroom community.

Just as customers must have an awareness of their requirements for a product, students must become aware of their educational demands. In completing Assignment 0, each student identifies his or her learning objectives for the course. Defining these objectives is beneficial to the student as it promotes initiative and develops a sense of commitment [5]. This marks the first time that students are actively involved in the development of their learning in this class.

Assignment 0 serves as the foundation for important themes encountered throughout the semester, like the need for boundaries, context, and focus. Establishing goals in this assignment effectively bounds what students set out to accomplish in the course; identifying personal backgrounds, experiences, and interests provides context for the achievement of those goals, and rank-ordering the goals determines how students focus their effort. It is easy for students to recognize the significance of these themes and extend them to the realm of engineering design. The Teaching Associate reflects on his first experience with Assignment 0:

> *Assignment 0, and its subsequent additions, provided me with a framework in which I could grow. I outlined goals, aspiration, and passions. Without a clear vision of where I wanted to go, how would I get there? Looking back at Assignment 0 (and having revisited it twice during the semester) I have recognized the importance of its input into my learning.*

This assignment is of most importance to the course orchestrator in the quest for mass customization of course material. Using Assignment 0 as a guide for each student, the

orchestrator becomes familiar with each student's background and interests and is therefore able to present class material in an individualized manner while providing personalized examples. For instance, to help a materials engineering student understand the mechanical design process, the orchestrator casts principles in terms amenable to the more familiar task of developing polymers and composites. The orchestrator also took special care in probing students that had expressed future ambitions with questions relevant to their future field. One such student, The Professor, offers this insight into the benefit of Assignment 0:

> *The questions that were asked in Assignment 0 helped to explicitly state the goals for each person in the class. Assignment 0 laid the framework by which each student would create their own course. This is the first stage of mass customization of ME 6101.*

Much like a diary, Assignment 0 is a "living document." Students are encouraged to revisit it throughout the semester in order to update their inevitably changing goals and aspirations. It is also suggested that they continuously reflect back on this assignment in order to take stock of their learning with respect to their personal aims. The orchestrator, too, tracks the changes in Assignment 0 such that course content can be personalized appropriately.

C. The ORA Learning Construct

As a designer of a system to be mass customized, an understanding of customers' requirements is not sufficient – it must be accompanied by an understanding of the drivers, or motivation, for the specifications. Professors face the same conundrum in the design of a course; in order to effectively choose efficient and appropriate methods of orchestration, a thorough understanding of the manner in which each student learns is required. This can prove to be difficult as many students have not articulated, let alone observed or reflected upon, their own distinct learning style. For this reason, it is necessary for the student to become cognizant of the manner in which they learn.

A key concept in ME 6101 is the Observe-Reflect-Articulate (ORA) construct, which is depicted as a three-section polygon in Figure 1. ORA signifies three crucial steps to learning, namely:

- *Observation*, in which ideas and information are absorbed from all available sources;
- *Reflection*, in which background knowledge and experiences are called upon to generate new ideas and connections; and
- *Articulation*, in which observations and reflections are stated and new conclusions and learning explained.

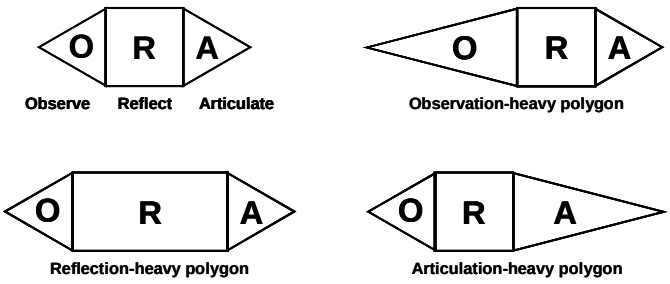

Figure 1. ORA polygon and its various shapes

The ORA construct exists in alternative forms as described by other authors. For instance, Bauer [6] offers the notion that learning consists of analysis, review, and synthesis; Evatt [7] suggests a "Creative Loop" that includes generation, investigation, and evaluation, and Kolb [8] describes a learning cycle composed of experience, reflective observation, conceptualization, and experimentation. But, ORA is unique in that it emphasizes the articulation of learning, which potentially makes higher-level cognitive tasks – specifically, analysis, synthesis, and evaluation as defined by Bloom and coauthors [9] – more tractable.

Early in the course, ORA is introduced to the students as a model for processing information in any task - engineering-related or otherwise. Students are urged to keep the ORA construct in mind and duly represent all three steps in their work. Further, they are encouraged to explore the use of ORA polygons having different shapes from that to which they are accustomed. That is, different amounts of observation, reflection, and articulation can be utilized, as illustrated in Figure 1. Many students comment on the ORA construct, evidenced in the following excerpts:

> *… with the introduction of Observe-Reflect-Articulate (ORA) [the orchestrator] has given me a technique, a mental model, which can assist me in creating my own knowledge. ME 6101 is most valuable in that it doesn't merely identify the important issues concerning learning and design but that it presents techniques and methods that are effective means to an end.*
>
> – The Philosopher

The ORA polygon is a mental construct that gives discipline to a normally meandering thought process. This is a great way to gain insight into one's own style and methods of processing information. I found that I was not the balanced thinker I imagined myself to be; I was heavily weighted on the Observation and Articulation sides. From my first encounter with this tool alone I was able to gain insight into myself and focus my efforts on improving the lacking Reflection part of the polygon.

– The Chief Executive

I am very much interested in teaching in the future, and working in projects related to the environment. I have had this desire for some time now, but because of this course I have had the opportunity to Observe-Reflect-Articulate more on this issue of my goals and values.

- The Green Engineer

The ORA learning construct is a vital part of the customized classroom. With its introduction, students have the power to effectively articulate their understanding. This in turn provides the professor a greater understanding of the student as a whole. With an understanding of the manner in which learning takes place, the students are empowered with the ability to provide customization at their own level – they are able to stretch their ORA polygon as needed to assist them in solving an infinite number of problems.

This class has shown me how I can incorporate ORA in everything that I do. Therefore I can learn from everything in my life, it is a matter of effort.

– The Philosopher

With an understanding of the customers (students) established, techniques of mass customization are ready to be implemented into the design of the product (course). In the next section we present approaches employed by the course orchestrator to customize the course.

III. MASS CUSTOMIZATION IN ME 6101

A mode for managing product variety is a generic approach in the design or manufacturing process to realize a customized product [10]. Basic categories of modes for managing product variety include, but not limited to, modular design, platform design and standardization, robust design, dimensional customization and adjustable customization. In our comparison to education, the techniques we present in this section serve as our modes for managing *student learning* variety.

A. Presentation Style

As the facet of course design which provides the orchestrator with the most direct contact with the students, the lecture period is one of the most important to modify for mass

customization. This subsection provides many subtle changes that can be made to the typical lecture period to add a customized learning experience for each individual.

It must be made clear that in the context of this paper there is a key distinction between "teaching" and "orchestrating." In the classroom, an educator should not act as the source of all knowledge, but rather as an architect of content who motivates students and provides the necessary scaffolding to facilitate learning. The orchestrator in ME6101 strives to do just this: "orchestrate" learning for each individual. Instead of teaching rote facts, the orchestrator provides students an opportunity to learn for themselves. This includes foundational facts, a method to learn how to learn, exercises to gain practice learning how to learn, followed by feedback. The Philosopher related this ideology to that of Socrates' description of a "mind-midwife" – one who helps those pregnant with knowledge to give birth it within themselves.

One orchestration technique that enhances the orchestrator's ability to provide individualized material is the use of lecture slides in Micrososft Power Point. Developing such a set of slides provides several advantages over the conventional "chalk and talk" approach, described as follows.

- Utilizing computerized lecture slides allows the professor to spend more time attending to students' individual needs and reactions. By observing student cues, the orchestrator is able to adjust the lecture (e.g., speed, emphasis, explanation, etc.) in order to deliver the material more effectively [11].
- The students are provided with hardcopies of the lecture slides in advance. In the absence of constant note taking, students are less likely to make mistakes from

copying down copious notes [12]. Perhaps more importantly, they are able to attend fully and keep pace with the orchestrator.

- Students are afforded the opportunity to personalize their hardcopies of the lecture slides and reflect upon the subject matter during class. While the orchestrator elaborates course content, students may generate and document ideas that are more meaningful or personally relevant.

The lecture is organized in a number of brackets. As each bracket is completed, the orchestrator orchestrates a brief discussion of the material in the bracket. This type of exchange is important as it allows the orchestrator to gauge the students' understanding of the material. Students who are more accustomed to taking notes or passively listening are instead prompted to think deeply on the spot and actively participate in such dialogues. Further, it gives the orchestrator a chance to personalize the discussions such that the unique interests of each student are considered. To facilitate these exchanges, the orchestrator utilizes several verbal cues in the form of questions:

- *How are you today?* Responses to this question indicate who is ready to learn and who is pre-occupied with other matters.
- *Do you follow?* The orchestrator asks this question to determine not only student attitudes about the material, but also their understanding of it.
- *What have you learned?* In answering this question, students articulate the various aspects of what they learned regarding the particular material presented in class.
- *What are you taking away from this?* Students respond to this question by identifying how they might relate the lecture content to, e.g., their past experience, design project, other areas of their lives, etc.

Students come to be familiar with these frequently asked questions, and are soon comfortable responding and articulating their thoughts in classroom discussions. This type of dialogue empowers the students to become more proactive in their learning [12]. From the desire to become a future professor, The Professor commented on how a typical lecture was orchestrated:

> *The learning atmosphere in the course is one in which students must be involved, material is not delivered in strictly a lecture basis. Students take part in exercises, discussions, and forums in class to maximize their learning.*
>
> - The Professor

Customization techniques are not limited to just the presentation style, however. As can be seen in the following subsections, customization of course material can take place outside of the class as well.

B. Learning Essays

In addition to periodic assignments, students of ME 6101 are faced with weekly learning essays. At the end of a day's lecture, the discussion points from each lecture bracket are reviewed and recast as suggested themes for the essays. Some of these themes include, e.g., describing the engineering design environment of the year 2020 and exploring ways that ethics can be infused into a systematic design process. In these essays, students address their feelings about their own learning as the course progresses.

Thus, learning essays serve as the main avenue in which students customize the course for themselves.

Learning essays are a means that encourage students to become reflective practitioners [13]. A rigid format for writing these essays is not given, and students are by no means limited to only the suggested themes. In fact, creativity and the application of course material to topics outside of engineering design are encouraged. During the Fall 2000 semester, a student applied Quality Function Deployment [14] to the purchase of a new pair of shoes; another related systematic design methods to the fable of the "Three Little Pigs"; and, a third student used the Pahl and Beitz design method to plan a wedding reception. The opportunity given to students to apply course material to their personal interests through learning essays is one facet in which this type of assignment provides a customized course experience.

Some suggest that such an absence of strict instructions in an assignment fosters creativity [5]. Others suggest that tasks must be open-ended and free from instructor evaluation in order for creativity to flourish [15]. The orchestrator in ME6101 embraces both of these principles when evaluating learning essays. They are read, commented upon, and returned to the student, but no grades are assigned; instead, the orchestrator indicates where new learning is evidenced or further exploration is needed. The personalized grading of each student's learning essays provided the orchestrator the opportunity to further customize the course experience. As students completed learning essays over the weeks, the professor was able to provide unique, personalized guidance to each student and was able to help them internalize the material at an appropriate pace and understanding level. The absence of grading, the informal format of the learning essays,

and the personalized comments seem to nurture creativity and accommodate individual learning preferences.

> *The assignments and essays focused our efforts and did not confine. We had the flexibility to experiment and take risks. These would have been risks if grades were assigned. No grade was assigned but the level of quality was assessed. [The orchestrator's] and [the teaching assistant's] comments helped me focus my efforts. The comments are more beneficial than a simple grade could ever be.*
>
> - The Philosopher

In writing a learning essay, students develop a deeper understanding of the material. This owes in part to the organization and clarification of ideas that takes place during the writing process. "Writing provides a uniquely penetrating probe into thinking processes … [and] … can provide strong evidence of the presence, or absence, of mature and creative thought" [16]. The discoveries made while writing are real and unique to students because they reflect upon the course content in a direct and personal way – thus the heart of this mass customized course.

C. The Use of "Best Practices"

Another customization technique used by the orchestrator of ME 6101 is the feedback sessions given periodically, called "Best Practices." For this to work it is important to ensure that students have bought into the notion of collaborative learning in a setting that

is non-competitive and one that encourages risk taking. In these feedback sessions, the orchestrator highlights examples of work, thoughts, or ideas that have been articulated by students in their assignments and essays. Students perceive their work to have value when it is displayed and discussed in class [17]. Additionally, students can add value to their work by reviewing "Best Practices." Reproducing, distributing, and reviewing such work in class provides students with particular examples of what they might like to do, or ideas to build upon in future assignments.

The practice also proves to be an effective method of reinforcing important points that should be learned. Sharing student work in a group setting helps classmates get to know one another better [18], which is often a personal goal that students list in Assignment 0. In reading and discussing the work of their peers, students discover not only other points of view but also new ways to express themselves. The Philosopher noted the importance of this technique in an essay:

> *[The orchestrator] has allowed us to experience quality/superb work of the other students through distributing best practices. I feel that the best practices assisted my learning, by focusing my efforts in the right direction.*
>
> – The Philosopher

Utilizing such examples also assists the orchestrator in providing personalized course feedback. The Teaching Associate noted:

> *By reviewing satisfactory work, the students were not only given concrete examples of what to do, but it was also an effective method of reinforcing the important points that needed to be learned. While some students may have found this exercise to be less exciting than others, little did they know that they were subconsciously internalizing the material … [The orchestrator] informed me that he chooses specific learning essays as "Best Practices" because he feels that one student in particular will benefit from it. I have realized that is not just an effective tool to show students what you are expecting as a professor, it is also a tool to orchestrate an individual course in a group setting.*

Through the use of computerized lecture slides, classroom discussions, assignments, learning essays, and shared coursework, course material is customized to each student. These instructional techniques are employed to help students make personal connections with the lecture material. In the next section, the benefits from having mass customized ME 6101 are presented.

IV. THE BENEFITS OF MASS CUSTOMIZATION

A. Students as Open Systems

Used in many different fields of study, the term "open system" has been used in operations management, computer science, marketing management, and design. The

term first originated within the biology community - a biological open system is one that exchanges energy and matter within its environment. Each subsequent application of this term in various fields focus on the basic premise that an open system is one that is *open to change, capable of adaptation and evolution, and is oriented towards growth.*

In design, this is no different. Simpson and co-authors [19] define *Open Engineering Systems* as "systems of industrial products, services, and/or processes that are readily adaptable to changes in their environment which enable producers to remain competitive in a global marketplace through continuous improvement and indefinite growth of an existing technological base." Here the importance of adaptation to change and need for evolution of the system is again stressed.

As many disciplines have created a link to the open systems paradigm, one can easily establish a similar link to the cognitive development of students. Learning can be considered an open system on many abstract levels. Learning serves as a way of empowering students to become more open – the ability to discover and internalize new information will enable students to grow and to adapt to changing environments. Learning itself can also be thought of as an open system; the manner in which students gain new knowledge can evolve over time and can adapt to fulfill specific requirements.

Ideally students should become open systems through their education - not in the biological sense - but instead in the paradigm of learning. Upon completion of a course, students should not only internalize the course material but also learn about the learning process itself - thus adding to their repertoire of learning techniques. Through guidance, students should also learn how to adapt to change and how to continue to learn on their own.

Just as mass customization is a technique to realize an open engineering system, mass customization of educational methods can assist in the realization of students who are *open learners*. We define an *open learner* as a student who is capable of thinking critically, framing abstract problems, forming creative solutions to problems, identifying the crux of problems, and synthesizing large amounts of information – a student who is able to continue to learn for a lifetime.

In the earlier sections, we have provided different techniques for customizing a course. In the following sections we describe three additional methods for providing an individual course in a group setting with the aim of giving students an opportunity to become "open systems."

B. The Question for the Semester

One of five deliverables required at the end of ME 6101 is an essay in which an answer to the "Question for the Semester" is provided. The Question for the Semester, "*How should the Pahl and Beitz systematic deign method be augmented and personalized to support the realization of technical systems for a global marketplace in the year 2020?,*" asks students to challenge their internalization of the Pahl and Beitz method and to postulate the requirements of the design community of the future. This question provides a focal point for the diverse topics encountered in class, and all coursework is aimed at helping students answer it.

As of the first day of class, students are presented with steps for answering the semester-long "take-home exam:"

- *Describe your world of 2020*

- *Understand your world of today*
- *Postulate your method; one that you will be able to evolve into methods required in your world of 2020*

Students are assisted in the development of their answers through the manner in which the course structure mirrors these "steps," as can be seen in Table 2.

Table 2. Stages of lecture content in ME 6101

	OBJECTIVE	TOPICS
STAGE 1	**Introducing Pahl and Beitz**	Four phases of systematic design: • Clarification of Task • Conceptual Design • Embodiment Design • Detail Design
STAGE 2	**Supplementing Pahl and Beitz**	• Ideation techniques • Budgeting tools • Management & Planning tools • Selection tools • Quality Function Deployment
STAGE 3	**Challenging Pahl and Beitz**	• Mass customization • Value Engineering • The future of manufacturing • Game theory • Ethics • Axiomatic Design • Decision theory • Robust design

Based on all of their experiences with the lectures, assignments, essays, and design project, students articulate their vision of a design environment for the future. Further, they propose and justify any modifications of the systematic design method prescribed by Pahl and Beitz. Students have already addressed aspects of this question in their learning essays and project work. Thus, generating an answer to the Question for the Semester is – to some degree – a simple compilation of existing material.

The development of critical thinking skills in ME 6101 is centered around the Question for the Semester. Answering this question requires that students be able to internalize, understand, and evaluate the Pahl and Beitz design method. Provided with a set of alternative techniques, the students are then able to augment and revise the Pahl and Beitz method as they see fit. The skills necessary to carry out this task are honed earlier in the semester through assignments, learning essays, classroom discussions, and the semester-long design project.

> *By answering the Q4S, students are encouraged to critically evaluate an established method and look to the future to create their own knowledge. Students are encouraged to think for themselves and postulate about the future of engineering and design in significant ways.*
>
> - The Professor

The Question for the Semester provides yet another opportunity for students to take an active role in their learning process. Students customize the course material to their own personal projections and explore an augmented Pahl and Beitz of their own creation.

> *ME 6101 has given me the opportunity to dream about the year 2020 through the Question for the Semester, and thus have a more palpable and desirable dream for my own future.*
>
> - The Green Engineer

Finally, the Question for the Semester provides the students an opportunity to realize the importance and inevitability of change. Through the completion of their own, customized design methodology, students have first-hand experience of adapting and evolving knowledge to compensate for change.

C. The Semester Learning Essay

A semester learning essay is also required of each student at the end of the course. As a culmination of all the previous weekly learning essays, this final learning essay is meant to address a student's learning over the entire semester. The advent of a final learning essay forces students to take a step back and revisit the entire course. They are able to synthesize an entire semester's material and can make connections that were not presently obvious. The student also addresses how their learning style (in the context of ORA) has changed throughout the course of the semester. This acknowledgement and articulation of learning style and the content of their learning makes the students more conscious of the need to continually evolve themselves through scholarship.

> *Ultimately, I find I am a better observer, reflector, and articulator than before. I am a more aware, better-informed designer with a passionate curiosity that will drive me to new discoveries. ME 6101 has introduced me to many new design concepts and their applications via many individual modules, but the effects of this class go beyond the scope of engineering design alone. In fourteen weeks, I have learned to learn for a*

lifetime. In that respect this course has truly been greater than the sum of its parts.

– The Chief Executive

It is suggested that the semester learning essay be constructed around an appropriate theme, analogy, or metaphor. Here again, creativity is encouraged when selecting a context to articulate an entire semester's learning. Metaphors have included traveling, growth, philosophy, various sports, and even unique topics like Noah's Ark and a Rube-Goldberg machine. This creative approach to writing a summary of learning provides the student the opportunity to apply course material to a personal example. Other students choose to write their learning as a step-by-step run-through of each week of the semester. No matter what style of answer is adopted, the completion of the Semester Learning Essay requires students to make the material "their own" – which requires a thorough understanding and analysis of the course material. This customized deliverable allows students to personalize the material to illustrate understanding, and it is another example of an instrument of mass-customization.

The answering of the Semester Learning Essay requires to students to synthesize an entire semester-worth of course material. As a result, incredible statements of the realization of learning are usually expressed in these final learning essays:

I believe that the value of ME 6101 is the knowledge gained throughout the course and the ability to continue to gain more knowledge. The wonderful aspect about ME 6101 is the excitement that you leave with to

keep learning, and thereby increasing knowledge and value. ME 6101 allows students to postulate the future, formulate lifelong goals, develop a passion to learn, and encourage students to learn how to learn.

– The Professor

I find myself smiling in pure gratification for what I have learned in this class, the self-empowerment of my own learning. I have "firmed up" the importance of internalization as a method of learning, facilitated by ORA. And I have discovered a method of understanding and implementation, the Pahl and Beitz systematic design method and my augmentations, which can be applied to everything I do. I find myself smiling for the confidence I have built in my abilities to tackle abstract problems. This is something that I have sought to gain from attending graduate school. Upon undergraduate graduation I felt my learning was incomplete. I had been given a lot of information but was missing the confidence of how to relate it to my design process. I was familiar with some of the tools presented in class prior to the course but lacked the clarity of their effectiveness that I gained in ME6101. This clarity came from an understanding of the capabilities of the tools, which I gained through implementation.

- The Philosopher

D. Self-grading Scheme

With the self-grading scheme, another end-of-semester deliverable, students are required to develop a meaningful method of analysis and evaluate their own body of work accordingly. The orchestrator considers the student-created evaluations when assessing their learning. This is an effective instrument in encouraging students to take seriously the notion that the course is being offered to an individual in a group setting.

As with the other techniques of mass customization presented earlier, students have the freedom to tailor this deliverable to their needs and style, as long as value is present. Students typically evaluate themselves with a scheme that was designed from lessons learned in class lectures on selection of design alternatives. Each student's grading scheme is different, as it reflects his or her emphasis on different aspects of the course. Personal goals from Assignment 0 are reflected upon and evaluated. The ability to tailor this deliverable to the individual is another example of an instrument to orchestrate an individual course in a group setting.

Through the completion of this deliverable, students are taking a hands-on-approach in the evaluation of their learning progress. With such a customized approach to assessment, students recognize need for improvement and intellectual evolution. Through in-depth analysis of their own work, students become more aware of their semester progress, their ability to meet goals (both personal and class goals), and their learning style.

It is in this assortment of deliverables that students articulate the totality of their learning in ME 6101. When given such opportunities to write and talk about their experiences, they internalize the course content and make it their own. They exercise their ability to think critically, frame abstract problems, and synthesize large amounts of

material. An awareness of the need to evolve, adapt, and grow are resultant benefits of these opportunities. Hence, these deliverables are an extremely important part of the learning process of ME 6101.

V. CLOSURE

There is no doubt that offering engineering design as a customized course is a difficult endeavor; but we seek a means that render it efficient and effective. At this point, we return to the questions posed in Section I.C and the techniques first listed in Table 1. In the particular context of ME 6101, we provide answers to these questions and their anecdotal support below:

- *How might a course be tailored to suit each student's individual needs and learning style?* Every part of ME 6101 is crafted in some way to promote the sense of an individualized course in a group setting. The tailoring of the class begins with Assignment 0, in which students make explicit their goals and background. During lectures, the orchestrator targets questions and examples towards personal interests and provides individualized feedback through "Best Practices." Essays and assignments are avenues for students to explore course content on their own terms.

> *I see ME 6101 as the base model automobile. The syllabus, assignments, and class meetings were the chassis, body, engines, and wheels of the*

automobile. There are no options set by the instructor, only presented for use by the class. The options are chosen and augmented by each student. As mentioned previously, this freedom can be frustrating and can lead to disgust for ME 6101, or can lead to a passion and desire for ME 6101. If mass customization can do only one thing in education, it is bring excitement and passion to learning for each student. It inspires students, even unmotivated ones, to embark on learning that caters to particular interests. Mass customization is the futures of manufacturing, as we know it for both traditional engineered products and engineering students.

– The Professor

- *What sort of classroom environment and activities inspire students to become more active in their learning?* Through explicitly articulating personal goals for the semester through Assignment 0, students are quickly forced to take a hands-on approach to their learning experience. Through the internalization of the ORA learning construct, students become aware of how and why they learn. Through in-class discussion, students become participants in their learning experience. The answer to the Question for the Semester (Q4S) and the Semester Learning Essay empower students to apply their learning to their own personal vision of the future. The grading scheme forces students to take an objective analysis of their progress.

What are the main elements that make this course robust, mass customized, and a sustainable learning environment? To me the main

> *elements are the combination of assignments, learning essays, lectures, games, oral presentations, reports, and literature that [the orchestrator] provides that almost makes sure we find or have everything we need to embark us in our learning how to learn. In addition, and probably more important, [the orchestrator] makes us think about our goals, how to achieve them, and provides feedback and examples in class that address particular individuals of the class.*
>
> – The Green Engineer

- *How can students be empowered to learn how to learn such that they can continue to educate themselves in the future*? Students in ME 6101 find that the ORA construct is the key to learning how to learn. In particular, learning essays are the primary vehicle for applying the ORA construct to both design tasks, and activities outside of engineering. The three final deliverables discussed in this paper all greatly contribute to this pedagogical goal. Through the completion of these tasks, students are forced to test their creative thinking and their ability to synthesize material. They also recognize the importance for evolution, adaptation, and growth of themselves in order to continue to learn.

> *There is no doubt in my mind that I have indeed come a long way in achieving (to learn how to keep on learning about designing). I am now acutely aware of my own past experiences, and the knowledge and biases they bring. I consciously attempt to discipline my thinking via the O-R-A*

mental construct. My personal awareness in terms of who I am and what I want to achieve over the long run are much clearer now. Knowing how to begin and proceed with a design problem has given me added confidence as a designer.

– The Chief Executive

[T]he most important aspect of [my experience in ME 6101] was that I learned how to learn. I learned how to tackle a huge problem by providing focus and context. I learned how to organize my thoughts and actions by identifying value. I learned how to articulate my feelings with others … These skills are now internalized … they are second nature to me.

– Teaching Associate

As a point of summary we present Table 3, in which we list the techniques discussed as presented in this paper. Specifically, we illustrate what each technique is, how its use helped to orchestrate an individual course in a group setting, and its resultant benefit.

There is much to be done to empower students to learn how to learn. Our approach is anchored in the observation of Heraclitus, the musing of Leonardo, and the wisdom of Gretsky. There are, of course, many other ways of empowering students to learn how to learn. In our opinion, there is no single approach that can properly carry the encomium of being the best. Kipling put it correctly when he said (and the emphasis are in his

original) "…There are four and twenty ways of composing tribal laws and---every---single---one---of---them---is---right." [20]

Table 3. Responding to the issues of the mass customization of ME 6101

	What	How	Benefit
Assignment 0	An assignment for students to establish personal goals.	Through answering a series of questions and posting a personal home page.	Student learns value of setting goals. Through periodic update, student recognizes importance of change. Orchestrator learns students' goals in order to provide an "individual course in a group setting."
ORA	A learning construct built of Observe – Reflect – Articulate	Students become aware of personal learning style and discuss in learning essays and class.	Students' awareness of the flexibility of the ORA polygon gives them the ability to adapt to infinite problems. Professor becomes aware of different styles of learning of each individual.
Lecture	Typical lecture period in classroom – majority of course material is presented.	Lecture is modified "on-the-go" according to students' needs and level of understanding. Students become involved through in-class activities and exercises.	Students' particular needs are addressed through reception of their visual and auditory cues. Customization of lecture provides further internalization of material.
In-class Discussion	Specific questions are asked to gauge student understanding.	Discussion is focused towards application to specific student goals. Lecture is modified to provide further clarification where needed.	Students learn to articulate thought through discussion of material with their peers and the professor.
Learning Essays	Weekly essays on learning gained from lectures.	Although topics are suggested, students are free to express their learning through whatever means and on any topic in order to accomplish their learning objectives.	Students learn to articulate learning through writing. Improves writing and communication skills. Creativity is fostered. Students internalize material through personal application.
Feedback	Personalized comments from professor on assignments and learning essays.	Orchestrator provides individual feedback to guide students into learning.	Students' learning is orchestrated at an individual pace. Customized guidance provides students more insight into their learning.
Best Practices	Examples of work that are shared with the class.	Examples of work are chosen to show interesting ideas and points of learning. These are shown in order to direct others' learning.	Students are able to build on work done by other students in order to make new discoveries. Students also gain insight into how others learn.
Answer to Q4S	A semester-long take-home exam that asks students to postulate the future of design and provide a suitable design methodology.	Students apply semester learning to individual and personal ideas about the future. The question can be slightly modified to reflect a personal interest.	Students take active role in learning through personal application of material. Critical thinking skills are developed. Students recognize inevitability of change and need to efficiently adapt.
Semester Learning Essay	A summary of learning taken place during the semester.	Students synthesize course material to articulate their learning. Each essay is unique. The flexibility suits all learning styles and interests. Learning is related to personal metaphor.	Students observe, reflect, and articulate on their learning. Students apply course material and learning to personal metaphor, which aides in internalization. Students recognize need to intellectually evolve.
Self-grading Scheme	Students evaluate their semester's work through a personal analysis scheme.	Students create their own grading scheme to evaluate their learning. Students evaluate themselves based on personal and class goals.	Personal evaluation gets students involved in analysis of their semester progress. Students recognize personal strengths and weaknesses. Students realize importance to continual improvement, growth, and adaptation

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BIOGRAPHIES

Christopher Williams earned his Bachelor's degree from the University of Florida (High Honors) in 2000. He is currently pursuing a Ph.D. at the Georgia Institute of Technology with the aid of the George W. Woodruff Presidential Fellowship. His research interests include design for mass customization, product architecture development, and design education. Christopher's current research entails the development of a methodology for developing product families by managing multiple

modes of product variety through constructal theory. Filled with fervor for gaining new knowledge through research and sharing that knowledge through education, Christopher has a dream of becoming a professor once completing his degree.

Farrokh Mistree's design experience spans mechanical, aeronautical, structural, industrial, and software engineering. His research focus is on developing the means to enhance the ability of human designers to make decisions along a system realization time-line. He is particularly interested in learning how to *manage design freedom* associated with the design, deployment, operation, and support of *open* and *sustainable* engineering systems. Professor Mistree is responsible for two books and over 250 technical publications. Since 1992 he is a Professor at Georgia Tech. He received his Bachelor of Technology with Honours from I.I.T. Kharagpur, India in 1968 and his M.S. and Ph.D. from the University of California, Berkeley in 1970 and 1974, respectively. In 1999 he was the recipient of the ASME DED Design Automation Committee's Design Automation Award. In 2001, he was the recipient of the Jack Zeigler Woodruff School Outstanding Educator Award. He is a Fellow of ASME and an Associate Fellow of AIAA.

TABLES AND FIGURES
(to be included in the text)

Table 1. Instruments of orchestration for a mass customized course

	How might a course be tailored to suit each student's individual needs and learning style?	What sort of classroom environment and activities inspire students to become more active in their learning?	How can students be taught to learn how to learn such that they can continue to educate themselves in the future?
Assignment 0	X	X	
ORA	X	X	X
Lecture	X		
In-class Discussion	X	X	
Learning Essays	X	X	X
Feedback	X		X
Best Practices	X	X	
Answer to Q4S	X	X	X
Semester Learning Essay	X	X	X
Self-grading Scheme	X	X	X

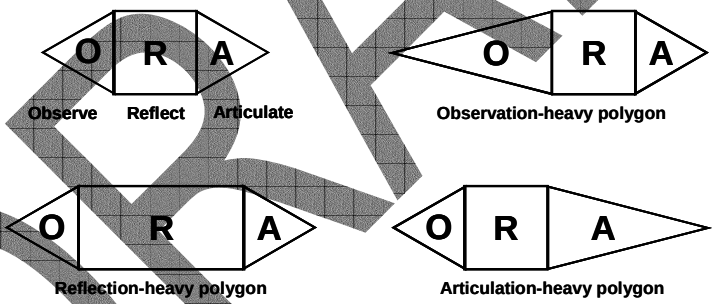

Figure 1. ORA polygon and its various shapes

Table 2. Stages of lecture content in ME 6101

	OBJECTIVE	TOPICS
STAGE 1	**Introducing Pahl and Beitz**	Four phases of systematic design: • Clarification of Task • Conceptual Design • Embodiment Design • Detail Design
STAGE 2	**Supplementing Pahl and Beitz**	• Ideation techniques • Budgeting tools • Management & Planning tools • Selection tools • Quality Function Deployment
STAGE 3	**Challenging Pahl and Beitz**	• Mass customization • Value Engineering • The future of manufacturing • Game theory • Ethics • Axiomatic Design • Decision theory • Robust design

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